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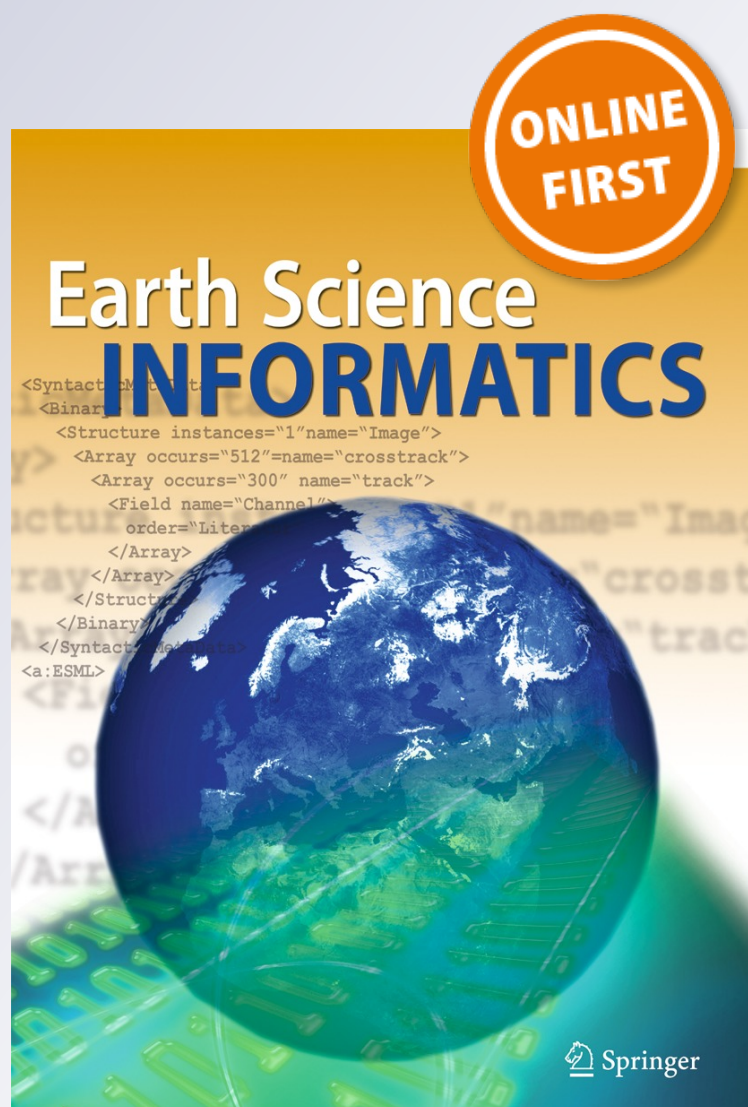
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Use of NTv2 transformation grids in engineering applications

Gabriele Garnero

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Abstract This paper describes a technique to transform coordinates between map references based on NTv2 format grids. Using the grids rather than carrying out a transformation allows to avoid map archives doubling, thereby easing “on the fly” transformation between different map representations. The paper also includes a case-study on a highway stretch currently under construction, the ‘Pedemontana Lombarda’ highway.

Keywords NTv2 · Rectilinear coordinates · Transformation grid

Introduction

The shift from one map basis to another expressed in different reference systems usually occurs through calculation processes which physically transform the archive of one system according to the representation system of the other.

All that is possible if the geodetic reference systems used are known, as much as the rules for mapping transformation adopted respectively. In this case, said transformation will allow information to be duplicated.

On the contrary, if the parameters defining the two reference systems and mapping representation are unknown, there are many mathematical transformation designed to permit the conversion of coordinate pairs from one map projection to another.

The simplest datum transformation method is a seven-parameter similarity transformation. The seven parameters

are three linear shifts (dx , dy , dz), three angular rotations around each axis (rx , ry , rz), and a hysotropic scale factor.

The Molodensky–Badekas method is a variation of the seven-parameter methods. It has three additional parameters that define the XYZ origin of rotation. This point may also be known as the origin of the datum, or geographic coordinate system. The XYZ origin of rotation point having been fixed, it is possible to calculate an equivalent Coordinate Frame transformation. The dx , dy , and dz values will change, but the rotation and scale values will remain the same.

The Molodensky method allows a direct conversion between two geographic coordinate systems without actually converting any datum to an XYZ system. The Molodensky method requires three shifts (dx, dy, dz), the differences between the semimajor axes (Δa) and the flattenings (Δf) of the two spheroids.

According to the methodology described, the main obstacle to the solution of the problem consists of setting parameters, which are usually fixed according to the least squares based on double coordinate points.

The solution is notably critical from the viewpoint of numerical calculation, as fixed parameters are negatively affected because of the geometrical formulation of the problem itself (double points on earth surface, usually in a relatively small area, with variables placed in the area around the center of the Earth) (Iliffe and Lott 2008) (Allan 2004).

It is also noted that the starting points for parameters setting themselves are affected by measurement estimates, this is why the calculated parameters will be obviously influenced by the quality of starting points.

In order to have an insight into said issues, it is possible to consult some interesting articles published monthly by Prof. Mounier on the website of Photogrammetric Engineering and Remote Sensing magazine in the section devoted to ‘Grids & Datum’ (<http://www.asprs.org/Grids-Datums.html>). Every

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month the datum of a State is analysed, with a clear outline of the main parameters defining the reference system.

For instance, the Italian case available at <http://www.asprs.org/a/resources/grids/08-2005-italy.pdf> includes an interesting chronicle of geodetic reference systems used in the country, in addition to some series of transformation parameters calculated by the European Petroleum Studies Group (EPSG), the International Association of Geodesy (IAG), and other bodies, to be employed for transformations involving 3 and 7 parameters

In addition to the equation-based transformation methods, grid-based methods can be employed: in the United States, the grid-based method is the most used to convert between geographic coordinate systems. The Grid-based methods allow the differences between the systems to be modeled and are potentially the most accurate. The area of interest is divided into cells. The National Geodetic Survey (NGS) publishes grids to convert between North American Datum (NAD) 1927, NAD 1983 and other older geographic coordinate systems (NADCON grids).

Similarly, also the method used in Canada to convert between NAD 1927 and NAD 1983 is grid -based.

The National Transformation version 2 (NTv2) method is quite similar to NADCON: a set of binary files contains the differences between the two geographic coordinate systems. A bilinear interpolation is used to calculate the exact values for a point.

Unlike NADCON, which can only rely on one grid at a time, NTv2 is designed to check multiple grids for the most accurate shift information. A set of low-density base grids exists for Canada. Certain areas, such as cities, have high-density local subgrids that overlay portions of the base, or parent, grids. If a point is located within one of the high-density grids, NTv2 will rely on the high-density grid; otherwise, the point will “fall through” to the low-density grid.

Unlike NADCON grids, NTv2 grids list the accuracy values of each point. Accuracy values can range from a few centimeters to around a meter. High-density grids usually have subcentimeter accuracy.

Australia and New Zealand adopted the NTv2 format to convert between geographic coordinate systems as well. Australia has released several state-based grids that convert between either Australian Geodetic Datum of 1966 (AGD 1966) or AGD 1984 and Geocentric Datum of Australia of 1994 (GDA 1994).

The state grids have been merged into countrywide grids. New Zealand has released a countrywide grid to convert between New Zealand Geodetic Datum of 1949 (NZGD 1949) and NZGD 2000.

The calculation of the grid-based methods are based on the knowledge of the geodetic parameters on which every representation is calibrated.

The methodology described in this paper allows on-the-fly transformations for the conversion of rectilinear coordinates (isometric coordinates generally used in engineering works, because they keep data measurable directly on Earth's surface) in cartographic coordinates systems and vice versa.

In this way, the transformations between the two systems can be completely implemented in a transparent way, thus avoiding the need for batch conversions and the resulting records duplication (Fig. 1).

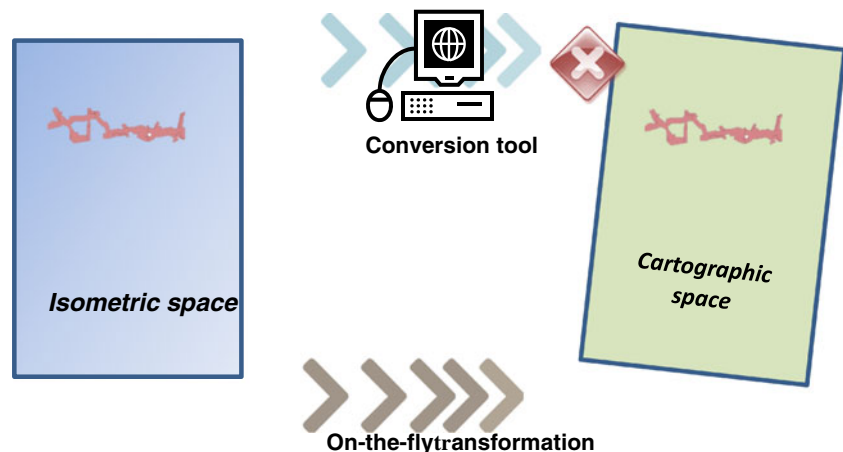
This standard methodology, first developed by the Canadian Geodetic Survey Division with the purpose of managing transformations between NAD 27 and NAD83 employed in the Country, is recognized by most desktop GIS software both commercial (ArcGIS®, MapInfo®) and Open Source (Proj4®, gvSIG®, QGIS®, ...), and is routinely employed in geographic coordinates transformation between standard formats.

GPS receivers also have relied on NTv2 grids for several years to provide transformation into a (possibly distorted) local coordinate system.

The grid-based methodology also allows to develop a single transformation software, thereby concentrating the peculiarities of every single problem on grid determination.

The originality of the present application stems from the fact that the common use of procedures involving the NTv2 grids is

Fig. 1 different systems of coordinate transformation



oriented to cartography type applications, with variations of the reference systems among cartographically processed systems.

In the case described as follows, an application is provided that involves an on-the-fly passage between coordinates in the rectilinear system used by designers, and cartographic coordinate systems that are ordinarily used in environmental monitoring applications and more generally in the core cartographic representations - a field in which scientific references are altogether lacking.

As a matter of fact, the reference found (i.e., (Ahrens and Böhmer 2010), (Brauner 2010) and (Natural Resources and NTv2 National Transformation software 2013) are all related to cartographic applications rather than to engineering and infrastructures applications.

The described application concerns the problems emerged during the setting phase of the environment monitoring system for 'Pedemontana Lombarda' highway, for which reference mapping data and environment monitoring data alike must be displayed simultaneously and clearly represented in the ordinary UTM/WGS84 mapping reference with the projected data of the roads which are instead described in the rectilinear coordinate system.

In addition to the description of the algorithms used and of the case-study, an overview will be given on the level of precision achieved and on the possible operational potential (Garnero 2012).

How the NTv2 format grid works

Similarly to the functioning of comparable types of transformation, the shift of points falling within a grid is calculated by bilinear interpolation between the four vertices of the cell (Fig. 2), while, no transformation or a transformation of different type (e.g., formulas of generalized type) is applied to points falling outside the grid, according to the settings and features used in the GIS environment.

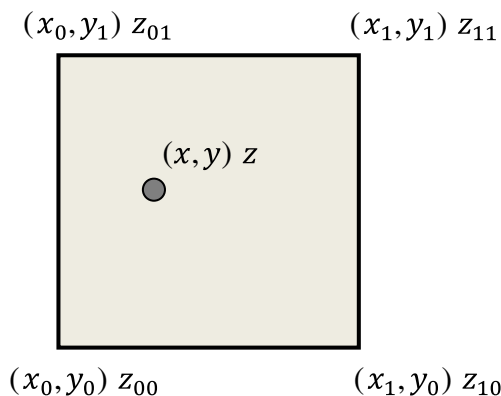


Fig. 2 Bilinear interpolation concept (see Mitchell and Collier 2000)

A given geographical area can be covered by several grids, possibly with different densities: a subsampled grid should be given at the lowest level. This is called “parent” grid, and covers the entire area, while in reduced portions of area there are subgrids with greater accuracy and point density (Fig. 3).

Considered:

$$\frac{x-x_0}{x_1-x_0} = s \text{ and } \frac{y-y_0}{y_1-y_0} = t \quad (1)$$

The calculation of a parameter z (in our instance both differences in the coordinate directions) results from:

$$z = f(x) = (1-s)(1-t)z_{00} + (1-s)tz_{01} + s(1-t)z_{10} + stz_{11} \quad (2)$$

or rather:

$$z = a + bx + cy + dxy \text{ with } a, b, c, d \text{ constants.} \quad (3)$$

Once the frame of reference system (also called “View Frame” or “Data Frame”, according to the terminology used by the software in use) is set, it is possible to display information layers, or themes, characterised by a reference system which is different from initial frame settings, on which an “on-the-fly” change is made.

The transformation is based on the bilinear interpolation described above, calculated based on NTv2 grids available.

NTv2 format specifications

The NTv2 grid format can be encoded as ASCII or Binary file.

The ArcGIS® software, used to carry out this project, requires binary formats; therefore, the developed procedure has required the production of a file in ASCII format and then the deployment of an NTv2 grid in binary form by an external application (Junkins and Farley 1995).

NTv2 files must start with a section that provides general information on the transformation (i.e. Overview) and a set of

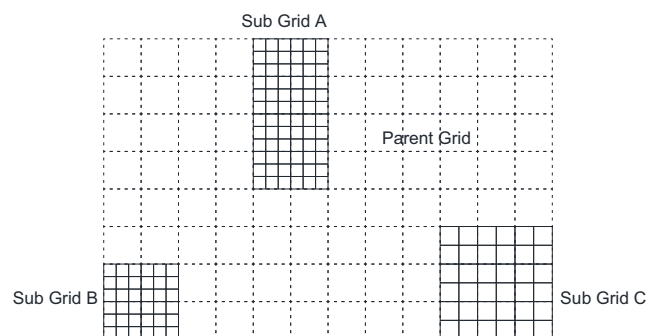


Fig. 3 Parent grid and Sub grid (see Mitchell and Collier 2000)

Record	Identifier	Value	Description	ASCII format
1	NUM_OREC	Integer	# header records in overview	%-8s%3d
2	NUM_SREC	Integer	# header records in sub grid	%-8s%3d
3	NUM_FILE	Integer	# of sub grids	%-8s%3d
4	GS_TYPE	String	Shift type (SECONDS)	%-8s%8s
5	VERSION	String	Distortion model	%-8s%8s
6	SYSTEM_F	String	"From" ellipsoid name	%-8s%8s
7	SYSTEM_T	String	"To" ellipsoid name	%-8s%8s
8	MAJOR_F	Double	"From" semi major axis	%-8s%12.3f
9	MINOR_F	Double	"From" semi minor axis	%-8s%12.3f
10	MAJOR_T	Double	"To" semi major axis	%-8s%12.3f
11	MINOR_T	Double	"To" semi minor axis	%-8s%12.3f

Fig. 4 Overview section of an NTV2 file

parameters necessary for the proper transition between the two systems, as listed below (Fig. 4):

NUM_OREC	number of lines making up the Overview header
NUM_SREC	number of lines making up the header of the sub-grid
NUM_FILE	number of sub grids used
GS_TYPE	unit of shift (default: seconds - sexadecimal seconds)
VERSION	Explanatory text string version

The following 6 records provide information about the input original datum (denoted by the suffix F meaning from) and the output one (with suffix T meaning TO) including geometric parameters describing the known reference ellipsoid.

After the "Overview" section, the file lists the subgrids, each one preceded by their relevant parameters (Fig. 5):

SUB_NAME	text string showing the name of the sub-grid
PARENT	parent grid name, or "NONE" in case of parent one
UPDATED and CREATED	ancillary information about the dates of creation and updating
S_LAT, N_LAT, and E_LON; W_LONG	minimum-maximum window, in geographical coordinates
LAT_INC and LONG_INC	grid intervals
GS_COUNT	total number of grid elements

Here follow the shift vectors, determining the transformation between the two systems.

Record	Identifier	Value	Description	ASCII format
1	SUB_NAME	String	Sub grid name	%-8s%-8s
2	PARENT	String	Parent sub grid name	%-8s%-8s
3	CREATED	String	Date	%-8s%-8s
4	UPDATED	String	Date	%-8s%-8s
5	S_LAT	Double	Lower latitude	%-8s%15.6f
6	N_LAT	Double	Upper latitude	%-8s%15.6f
7	E_LON	Double	Lower longitude	%-8s%15.6f
8	W_LONG	Double	Upper longitude	%-8s%15.6f
9	LAT_INC	Double	Latitude interval	%-8s%15.6f
10	LONG_INC	Double	Longitude interval	%-8s%15.6f
11	GS_COUNT	Integer	Grid node count	%-8s%6d

Fig. 5 Header of each grid

Where more than one subgrid is present, they are arranged in a sequence, and at the end of the file, there is an indication of END.

The grid is generated in the reference system of origin, defined in the current case study in the geographic coordinates of the rectilinear one, expressed in sexagesimal seconds, carefully handling signs and directions, taking into account that the original system has been designed for Canada, where latitudes are negative:

- $\Delta\varphi$ (positive increases the North coordinate): $(\text{Lat_WGS84} - \text{Lat_RETT}) * 3600$
- $\Delta\lambda$ (positive decreases the East coordinate): $(\text{Long_RETT} - \text{Long_WGS84}) * 3600$
- two pairs of zeros (precisions, not used in this work)

The expected format for each shift is F10.6 (Fig. 6).

The generated file in ASCII format with an ASC extension should be converted into binary format. To this purpose, the "gDay datum transformation (rel. 2.10)" software has been employed, available as shareware from the website of the Department of Natural Resources and Mines (Queensland, Australia), <http://www.derm.qld.gov.au/property/surveying/files/gday21iex.exe> (Fraser 2002).

This software contains several useful options for cartographic transformations, including conversions of NTV2 grid files from ASCII to binary and vice versa: the result is a file in GSB format which, allows the carrying out of the described procedure when placed in the ArcGIS® default directory for this type of transformation

The case study: the "Pedemontana Lombarda" highway

The "Pedemontana Lombarda" highway is a road infrastructure running through a largely urbanized, densely populated and heavily built territory, and it is formed by:

- 67 km of motorway, constituting the main axis from Cassano Magnano to Osio Sotto, in the connection between the A8 and the A4 north of Milan;
- 20 km of highway, connecting Varese and Como, respectively 11 and 9 km long;
- 70 km of associated road works, which are planned to contribute to the alleviation of congestion of local roads.

The core map was developed in 2008 based on an already available benchmark network, where the coordinates of the vertices, divided into 4 lots, were known also in rectilinear coordinates; on the other hand, the algorithm employed with the aim of calculating the rectilinear coordinates was unknown.

The current need to manage environmental monitoring, as early as the pre-operational stage, requires the availability of a methodology allowing rapid project coordinates conversion, expressed in rectilinear coordinates, to cartographic ones in

Diagram illustrating a 2D grid structure with nodes and intervals.

The grid is defined by nodes and intervals:

- Nodes:**
 - Node (M*N) at the top-left corner.
 - Node (N) at the bottom-left corner.
 - Node (1) at the bottom-right corner.
 - Node (N+1) at the top-right corner.
 - Node (2) at the center.
 - Node (N+2) at the center-left.
 - Node (2*N) at the center-right.
- Intervals:**
 - Latitude Interval:** The vertical distance between the top and bottom rows.
 - Longitude Interval:** The horizontal distance between the left and right columns.
- Row and Column Labels:**
 - row M:** The top row.
 - row 1:** The bottom row.
 - col N:** The left column.
 - col 1:** The right column.
- Latitude Orientation:**
 - Upper Latitude (North, least negative):** Indicated at the top.
 - Lower Latitude (South, most negative):** Indicated at the bottom.
- Longitude Orientation:**
 - Upper Longitude (West, least negative):** Indicated on the left.
 - Lower Longitude (East, most negative):** Indicated on the right.

The ArcGIS® project management environment allows to check for individual lots, produced and stored in rectilinear coordinates, superimposed on an “on-the-fly” basis with reference base layers such as orthoimages.

The grids have been partially developed by means of a dedicated software, and partially, with the aim of computing

files in binary format, by employing utilities retrievable in several websites.

In order to limit the magnitude of shift values to be applied for the transformation purposes (grids have been developed with performing transformations between different geographical datum, with values of the order of few seconds) a newly computed reference system has been defined.

It derives directly from UTM/WGS84 Zone 32, but with a different false origin, in order to minimize the deformation occurred during transformations in the ArcGIS® platform adopted. Deformation will then be handled by NTv2 during the projection phase with shift values changing from the initial values of 150,000" to those of the order of second-type units.

The false origin is calculated by taking a point roughly in the centre of gravity of Lot 3:

- Lot 3 centre of gravity, rectilinear coordinates [m]: 152, 500, 241,500
- Lot 3 centre of gravity, UTM/WGS84 [m]: 518,000, 5, 054,500
- Differences [m]: 365,500, 4,813,000

The resulting values are the following:

- False_Easting [m]: $500,00 - 365,500 = +134,500$
- False_Northing [m]: $-4,813,000$

Validation

In order to validate the obtained results, an analysis has been carried out using the limits of the different lots: vertex coordinates, initially expressed in rectilinear coordinates, have been extracted and the obtained values have then been compared with the results of an “on-the-fly” transformation, developed in the framework of the infrastructure plan and already employed by project designers.

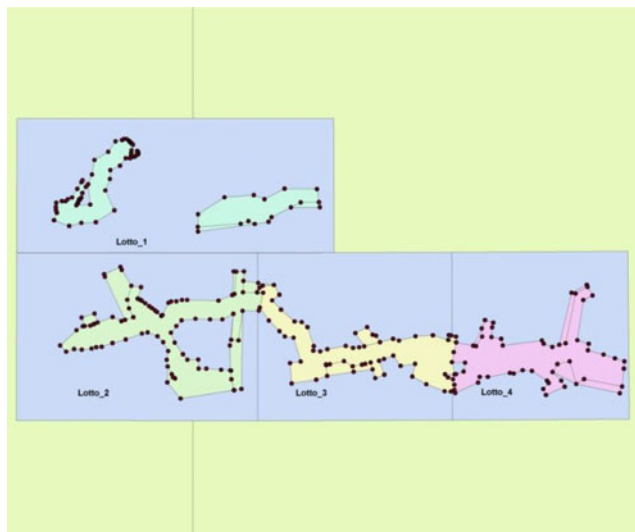


Fig. 8 Points used in validation, coincident with vertices of the lots

The residual analysis leads to the following considerations:

- for each point inside the rectangles, representing single lot (365 points out of 391 available), the differences are less than one millimetre and, consequently, the transformation can be considered fully responsive to the purpose (Fig 8);
- vertices that belong to a lot, falling within the rectangle of another one (26 points out of 391) show critical values, with average values of 5 cm, with peaks up to 9 cm, as they are transformed from values of the adjacent lot (Fig. 9);
- the induced deformations are considered acceptable within the needs of the project destinations, considering the field of employment of transformations (environmental monitoring);
- attention should be paid on the fact that the discussion on residuals concerns internal quality. It is only about the computational quality of the solution, not a real assessment of effects visible in the real world (e.g., when using the method for automatic guidance of construction vehicles);
- in addition, it should be noted that the example was developed next to the central meridian of the zone (9° approximately): in this area, the values of the “reduction at the ropes” are minimal even for distances up to 5 km. The result of the conversion will be correct also along the boundary of the zone, for example close to 12° of longitude.

Further developments

The use of the grid-based transformation method can be applied, as well as in engineering applications, also in other field of application (ESRI 2006).

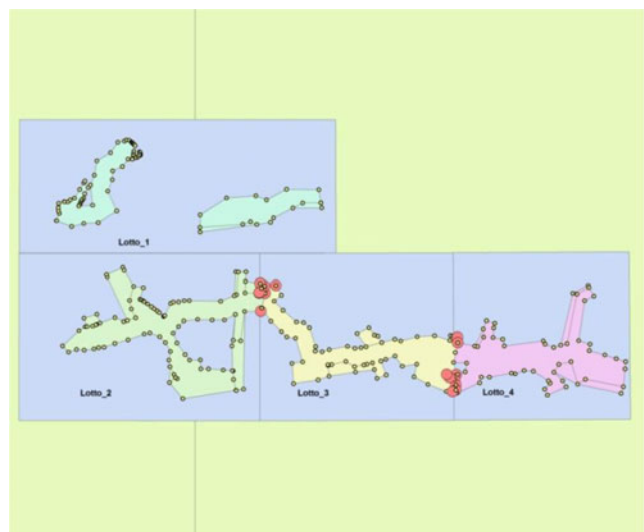


Fig. 9 Points with residual values > 1 cm

NTv2 grid files will be soon recognized as a standard in Italy: the IGM (*Istituto Geografico Militare*) recently started to release a version of its grids in such format, which will allow users to project “on-the-fly” maps expressed in different reference systems, without the employment of other official procedures usually adopted for data transformation in Italy (eg. Verto software, available on <http://87.30.244.175/software.php>) which are based on standard coordinate transformations.

Different applications are currently being developed in the cadastral field: in this case, a grid of points appropriately calculated and validated will make it possible to benefit from these techniques, effectively avoiding the supply of cadastral databases in multiple coordinate systems. Instead of providing maps in Cassini-Soldner and contemporarily in Gauss-Boaga and in UTM/WGS84, the cadastral administration will be able to provide only the maps in the ordinary format (i.e. Cassini-Soldner) and, by attaching the grid transformation, it will allow each individual user to display their maps in the desired reference system (Ahrens and Böhmer 2010).

Given the peculiarities of the context, particular attention should be placed to check for the validity of transformation results for each local system in cadastral applications. Note that, when using your method with cadastral data, you can preserve the metric integrity of the original data (that have legal value) while you can overlap with up-to-date maps.

An extremely interesting application of the above discussion is the use of these grids in raster files, for which ordinary conversion procedures cannot be used. For orthoimages, but even more for the DTM (Digital Terrain Model), it is extremely useful to have tools available that, do not require a new gridding to carry out the reference system conversion, but can be simply converted on-the-fly, without degradation of accuracy and without duplication of records.

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